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Tribological Optimization of Dry Forming Tools

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Abstract

Waste prevention and an efficient use of resources becomes more and more important in industry from both an economic and environmental point of view. Especially in forming processes such as deep drawing, lubricants are nowadays still an inevitable part to reduce the friction forces and to protect the tools against wear. Since cleaning of forming products is costly and time-expensive, a complete elimination of lubricants is desirable. Ultimately, the highest savings can be realized by a complete lubricant free deep drawing process – namely dry forming. In this paper, tribological optimization of dry forming tools for lubricant-free forming by means of a protective coating and micro-structuring of the tool is presented. While focusing on the improvement of frictional and wear properties, it is shown that ta-C coated tools operated in a dry environment can reduce friction up to 15% compared to the lubricated case. Moreover, it is outlined that a micro-structuring of the tool by Direct Laser Interference Patterning technology can significantly reduce the tools wear.

Keywords: Deep drawing, Dry Forming, ta-C coating, Direct Laser Interference Patterning

1 Introduction

Lubricants play an essential role in almost all metal forming processes since they reduce the interfacial forces between tool and work piece. Thus, friction is significantly reduced which in turn avoid cold welding of the paired surfaces. Moreover, their presence leads to an increased tool lifetime, a reduction in forming energy and overall to an improvement of the products surface finish. Hence, lubricants are an inevitable part of nearly all metal forming processes [1].

However, the improved tribological performance in presence of lubricants involves the economic disadvantage of additional costs mostly arising from the cleaning of parts and subsequent waste disposal [2]. Therefore, many efforts have been done to gradually decrease the amount of employed lubricants in industry. Unfortunately, approaches employing a strongly reduced amount of lubricating species showed no solution to the general problems provoked by the use of lubricants. Therefore, new concepts based on a complete lubricant free forming process came into focus – namely dry forming [3]. The most promising concept involves the use of protective coatings on tools to realize a lubricant-free forming process [2-6]. Although various studies show promising results under laboratory conditions, none of them can realize a total lubricant-free forming process [7]. Consequently, a forming process without any lubrication in an industrial application is of great interest and in the scope of the presented work.

In this paper, an optimization of the tool design for deep drawing applications is proposed by employing a functional coating in combination with a multiscale surface structuring to control friction, wear and material flow. As tool coating, a tetrahedral amorphous carbon (ta-C) film is used which combine a low friction coefficient and anti-adhesive behavior with a high hardness and wear resistance [8-12] originating from the disordered network of carbon atoms [13, 14]. The employed ta-C tool coating introduces a well-defined boundary layer capable of taking over the tribological functions of the lubricant while additionally providing protection of the multiscale macro- and microstructures [7]. The ta-C film is micro-structured by Direct Laser Interference Pattering (DLIP) method to further modify the tribological performance e.g. by reducing the interfacial contact area [15-17]. Finally, a macro-structuring of deep drawing tools in the flange area reduces the contact area between tool and work piece in

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comparison to unstructured tools. Thus, the applied macro-structures allow for reduced friction forces as well as control of material flow within the heavily loaded flange area, as shown in Ref. [7, 18]. In this work, the combination of ta-C coating and DLIP micro-structuring on forming tools will be investigated in terms of its tribological properties and long-term stability.

2 Experimental methods

2.1 Preparation of ta-C films and characterization methods

The ta-C films were prepared in a PVD coating plant MZR 373 by Metaplas Oerlikon (bias voltage up to 1 kV, mass-flow controlled gas environment, base pressure of about 8 x 10^{-4} Pa) [14]. Cylindrical draw-bend samples (length: 65 mm, diameter: 10 mm, 16 mm and 20 mm) made from cold work tool steel 1.2379 (X155CrVMo12-1, ASTM D2) were degreased, ultrasonically cleaned followed by a spray cleaning using an alkaline, rinsed with de-ionized water and isopropanol and finally dried. After mounting the steel samples in a single rotation, the vacuum chamber was evacuated down to a pressure of 5x10-2 Pa and heated three times for 5 minutes followed by plasma cleaning (6 times for 15 minutes). Subsequently a thin chromium layer was deposited as adhesion layer. Finally the functional carbon layer was deposited at a deposition time and temperature of 62 minutes and 85 – 190 °C, respectively. To avoid softening of the hardened samples by high process temperatures, the deposition was carried out in cycles containing pauses to cool down.

The carbon layer thickness was measured by calotte grinding whereas the chromium layer thickness was determined with the help of spectroscopic ellipsometry in the range between 350 nm and 1050 nm (step width: 10 nm; spot size: 1.5 mm; measuring angles: 65°, 70° and 75°) from pre-ta-C-coated samples. A mechanical profilometer with a dynamic range of 80 µm and a resolution of 10 nm was used in order to measure the roughness of the uncoated and coated surfaces while the modulus of elasticity was determined by using a laser-acoustic method (LAwave). Layer adhesion tests were done by Rockwell-C indentation and conventional scratch tests including a comparison with reference standards (ACC: adhesion class Rockwell C) and a determination of the critical loads (Lc2 – delamination at the scratch rim; Lc3 – first buckling cracks).

2.2 Direct laser interference patterning

The micro-structuring of surfaces was realized employing the DLIP technology. The DLIP processing was performed with a pulsed (wavelength: 532nm; pulse duration: 8-10 ns) solid state laser system in a two-beam setup [17] with a laser fluence of 0.4 J cm^{-2}. Briefly, the laser beam was divided into two sub-beams by a beam splitter configuration. Then, the sub-beams were overlapped on the sample surface with a specific overlapping angle β (see Fig. 1) which together with the laser wavelength determines the spatial period of the interference pattern. All experiments were performed with a single laser pulse under ambient conditions.

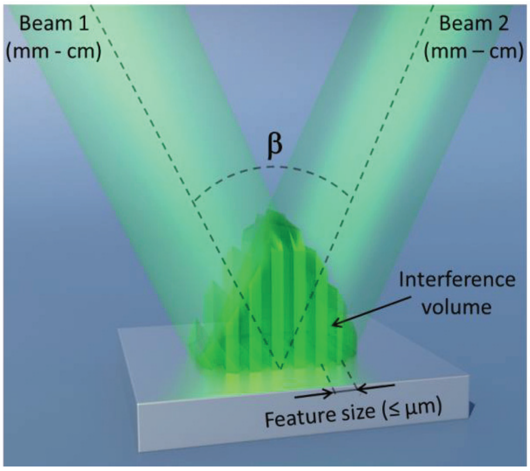

Figure 1: Schematic representation of the Direct Laser Interference Patterning technology for the structuring of materials. The shown two-beam configuration leads to the formation of a line-like laser intensity distribution.

2.3 Draw-bend tests

In order to determine the friction coefficient under conditions similar to those encountered in the real forming process, draw-bend tests have been used. These are especially relevant for the bending of the work piece at the die radius during a deep drawing process. Differential measurements of two subsequent tests were carried out - one by drawing the work piece over a fixed circular cylindrical tool-pin ensuring contact over an angle of approximately 90° with a constant predefined velocity, the other over a freely rotating pin, with the understanding that no sliding takes place. The difference in front tension measured in two tests gives an estimate of the friction. A schematic view of the fixed circular cylindrical tool-pin setup can be found in Ref. [19]. According to the belt friction theory, friction coefficient between tool and strip can be calculated by

$$\mu = \frac{2}{\pi} \cdot ln\left(\frac{F_1 - F_b}{F_2}\right),$$

where F1 is the pulling force, F2 is the back tension force and Fb is the force due to bending. The tensile forces F1 and F2 were measured simultaneously during the test.

3 Results and Discussion

3.1 Layer characterization

Tab. 1 summarizes the results of the layer characterization where all given values (except the thickness of chromium interlayer, which was taken from uncoated samples) originate from coated flat steel reference samples.

Note that as-deposited ta-C coated samples typically exhibit a high surface roughness due to the inherent characteristics of the ion deposition process [8]. Hence, coated tools were brushed for 5 min using a wire brush (low alloy steel, wire diameter of 0.2 mm). The used brush force was 5 kgf (i.e. 50 N), the rotating speed of the wire brush was 6,000 rpm and that of the tool – rotating contrarily – was 150 rpm. No additional abrasive was used.

Table 1: Results of layer characterization of the as-deposited ta-C film

	layer thickness		layer roughness		elastic modulus	adhesion		
rotation	d(Cr) /nm	d(ta-C) /nm	Ra /nm	Rz /nm	E / GPa	Lc2 /N	Lc3 /N	ACC
1-fold	80	2590	530	3080	350	25.93	22.38	2

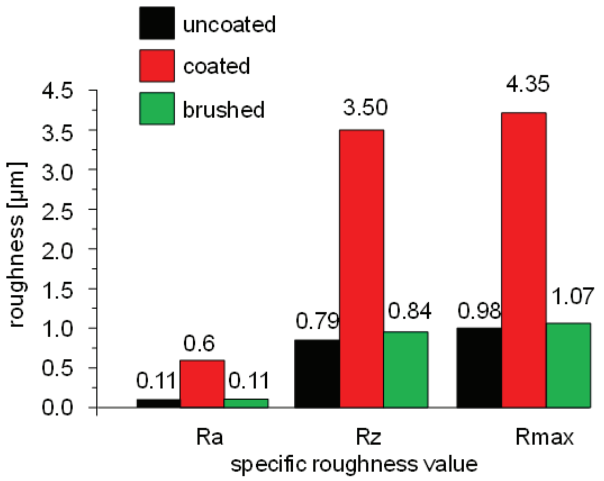

Figure 2: Mean values (average of 15 tools) of specific roughness values Ra, Rz and Rmax for the uncoated (green), coated (red) and brushed (green) surfaces.

No changes in coating thickness were observed, as concluded from calotte grinding prior and after brushing. Fig. 2 exemplifies that the surface roughness of the coated tools in terms of Ra, Rz and Rmax can be reduced down to the roughness of the uncoated surface by brushing. Note that an additional brushing does not lead to a further reduction in surface roughness. Finally, the ta-C coated and brushed draw-bend tools were used for DLIP micro-structuring.

3.2 DLIP processing of ta-C coatings

As part of the DLIP micro-structuring, a line-like pattern with a structure period of $\Lambda = 10$ µm was applied on the functional surface of the ta-C coated draw-bend tools, as shown in Fig. 3. The introduced micro structures show a periodic topography on the ta-C surface where red areas correspond to structure heights of ~250 nm. The change in topography originates from a local $sp^3 \rightarrow sp^2$ rehybridization which results in a local decrease of material density and the development of line-like surface elevations. The change of the sp^3/sp^2 ratio was determined by a Raman spectroscopy analysis, where laser-irradiated (interference maxima) and non-irradiated (interference minima) areas were compared [19]. Additionally, no thermal diffusion from the interference maxima to the interference minima positions was bserved within the Raman spectra [15]. Consequently, the DLIP-structuring introduces a periodic variation of sp^3- and sp^2-rich regions which are expected to impact the tribological properties during the draw bend tests.

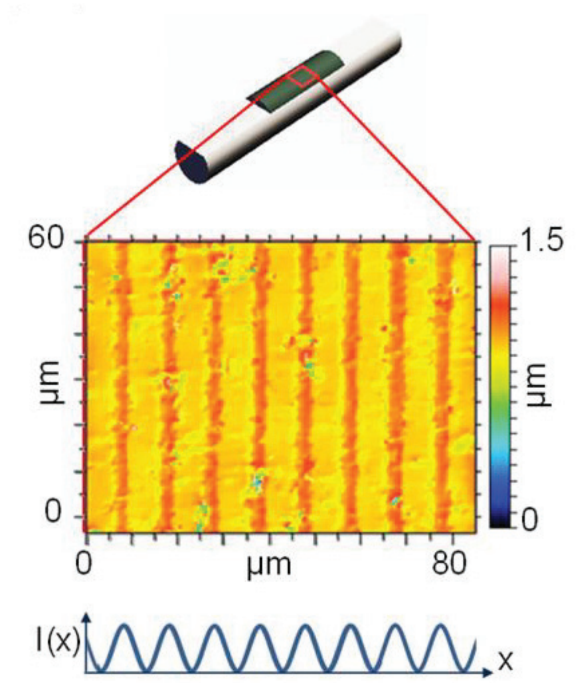

Figure 3: Schematic sketch of the draw-bend tool which was structured by DLIP. A line-like pattern with a structure period of $\Lambda = 10$ µm results, as determined by confocal microscopy. The intensity profile I(x) of the laser is also indicated.

3.3 Draw-bend tests

The tribological characteristics of the ta-C coated and DLIP-structured cylindrical specimens were investigated by draw-bend tests. The tests were carried out at room temperature with a constant drawing velocity of 100 mm/s and a contact surface pressure of 50 MPa. The unstructured/coated as well as DLIP-structured/coated specimens were tested under dry conditions. Uncoated tools were measured under dry as well as wet conditions (lubricating oil “WISURA ZO 3368”) as a reference. Work-piece strips were cut from commercially-sourced DC04 steel (1.0338) of 1 mm thickness, 20 mm width and 1000 mm length. Each strip was cold-rolled, cleaned using a citrus based cleaner and finally treated with acetone to remove all traces of pre-lubricants. Each tool was subject to 100 draw-bend tests corresponding to an effective testing distance of 40000 mm (or 1100 caps with 50 mm diameter). The resulting average friction coefficients with the range of results (shown as vertical bars) are presented in Fig. 4a.

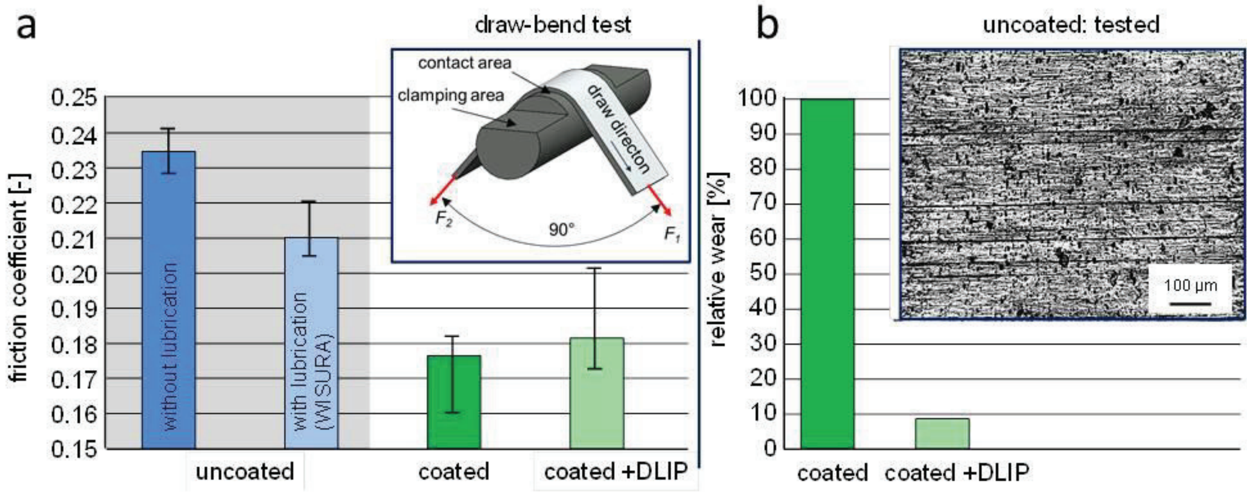

Figure 4: (a) Friction coefficient resulting from the draw-bend test of uncoated tools (dry/lubricated conditions) as well as coated and DLIP-structured/coated tools. Inset: schematic overview of draw-bend test. (b) Comparison of relative wear between ta-C coated and the coated/DLIP-structured draw-bend tools measured by white light interferometry, Inset: Optical micrograph of uncoated surface (lubricated).

The highest friction coefficient was observed for the uncoated tools under dry conditions accompanied by severe wear of the tool surface. As expected, the friction coefficient is reduced from 0.24 to 0.21 (~12 %) in presence of a lubricant (“WISURA ZO 3368”). For comparison, coating the tool with ta-C reduces the friction coefficient to ~0.18 (dry conditions) which is about 25% and 15% less than in the uncoated case under dry and lubricated conditions, respectively. The draw-bend tests of the ta-C coated and DLIP-structured tools show a slightly increased friction coefficient (~0.18) compared to the coated and unstructured tool.

However, a detailed analysis and comparison of the unstructured and DLIP-structured ta-C coated tools after the draw-bend tests by means of white light interferometry indicate a significant reduction of worn material (~90%), as summarized in Fig 4b. The reduced wear is attributed to the modified sp^3/sp^2 ratio at the tribological interface where sp^2-rich elevations act as an enhanced shear interface accompanied by shear localization which in turn acts as a protection of the underlying ta-C surface [13].

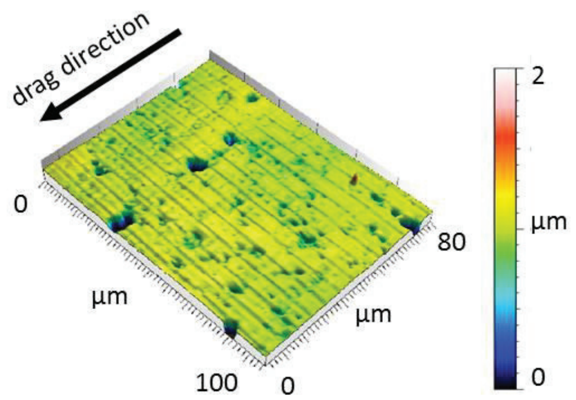

Figure 5: Confokal micrograph of a ta-C coated and DLIP-structured surface after 100 draw bend tests.

Note that the sp^2-rich elevations on the DLIP-structured tool persist even after 100 draw-bend tests, as shown in Fig. 5. Future work is necessary to clarify the underlying mechanism behind the observed wear reduction.

4 Summary and Conclusion

In this paper, the tool optimization for dry forming applications was presented. Draw-bend tools have been coated by tetrahedral amorphous carbon (ta-C) films by PVD coating. As-deposited ta-C films had a thickness of about 3 µm, an elastic modulus of 350 GPa and a relatively high surface roughness. By brushing, the surface roughness was significantly reduced down to values comparable to the uncoated samples. Draw-bend experiments performed with the ta-C coated tools showed a reduction of the friction coefficient up to 15 % compared to the uncoated case under lubricated conditions. A micro-structuring of the ta-C coated tools by Direct Laser Interference Patterning (DLIP) employing a line-like pattern and a structure period of Λ = 10 µm showed further modifications of the tribological performance. The DLIP-structuring leads to a local variation of the sp^3/sp^2 ratio as a consequence of the laser-induced $sp^3 \rightarrow sp^2$ rehybridization at the interference maxima positions, as determined by Raman spectroscopy. While draw-bend tests of the DLIP-structured tools showed only minor impact of the micro structuring on the frictional properties, the wear behavior was significantly modified. The draw-bend experiments revealed a reduction of the worn material by ~90% compared to the unstructured and ta-C coated tools, as measured by white light interferometry. This is attributed to the modified sp^3/sp^2 ratio at the tribological interface, where sp^2-rich elevations lead to shear localization and consequently to an enhanced shear interface. As a result, ta-C coated and DLIP-structured draw-bend tools show highly promising tribological properties even on a long-term scale. Future work will focus on the origin of the reduced wear.

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